TM-70-2032-1

TECHNICAL MEMORANDUM

CREW FATIGUE LIMITS FOR APOLLO OPERATIONS

Bellcomm

BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Crew Fatigue Limits for Apollo Operations

TM- 70-2032-1

DATE- June 30, 1970

FILING CASE NO(S)- 320

AUTHOR(S)- T. A. Bottomley

FILING SUBJECT(S)-
(ASSIGNED BY AUTHOR(S)-

ABSTRACT

This memorandum covers the results of a study performed to define the effects of fatigue as they limit the Apollo crew's capability to work during lunar exploration missions. It includes also discussions of data in which environmental and temporal factors of heat stress and sleep deprivation, respectively, are shown to have a marked influence on establishment of fatigue boundaries.

The fatigue limits, for unstressed EVA crew members working at an average metabolic rate of 1000 Btu/hr, are established at about 5 hours to onset of fatigue and about 8 hours to the end-point of useful work. To ensure more accurate trending of consumables usage and more reliable crew performance, it is proposed that the onset-of-fatigue limit be considered a firm operational constraint for planning purposes. It is suggested that this constraint be imposed with the understanding that this limit can be relaxed in real time up to the boundary defining the limit for useful work in order to accomplish important mission objectives if permitted by crew condition and future planned activities.

Measurable reduction in human performance is commonly observed after 20 hours continuous awake time. To combat the effects of sleep deprivation, work/rest guidelines are suggested for operational planning purposes. Briefly, it is proposed that:

a) nominal operations be planned for a duty day of 24 ± 4 hours including an 8 hour uninterrupted sleep period, and,

b) pre-planned emergency procedures provide for a day-length not exceeding 30 hours including a total of 6-hours sleep for each crew member to be accumulated at times which are most appropriate.

ABSTRACT - continued

The fatigue limits proposed in this report have been established by extrapolation from available information in the literature which is sparse. Additional data are needed to improve understanding and to make the boundaries more precise. Tests conducted under non-stressful conditions with subjects working at light to moderate steady-state metabolic rates over a period of twenty hours should be considered by NASA to obtain meaningful data. The underlying objective would be to increase confidence that LEP goals can be achieved without incurring additional risk as a result of degraded operational capability on the part of the crew.

BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

SUBJECT: Crew Fatigue Limits for Apollo Operations - Case 320

DATE: June 30, 1970

FROM: T. A. Bottomley
TM-70-2032-1

TECHNICAL MEMORANDUM

INTRODUCTION

An operational goal in LEP is to maximize time on the lunar surface in order to realize a high scientific yield on each mission. To attain this goal it is necessary to know the EVA time constraints imposed by the performance limits of the man as well as his supporting hardware. One physiological factor which requires better definition to permit extending EVA surface time beyond five hours is fatigue.

There are two principal reasons why quantitative limits for fatigue are needed. These are:

1. to permit more accurate predictions in realtime of consumables usage during EVA, and

2. to insure that crew risk is not increased due to deterioration of astronaut performance.

Both reasons assume even greater importance in the event of an emergency.

The arguments for these concerns are illustrated in Figure 1 which is constructed to show the impact of fatigue on the trended time course of oxygen, water and LiOH usage during a lunar EVA traverse. The external workload is considered to be constant such as walking over level terrain at a fixed velocity. It can be seen that failure to take into account an increase in energy expenditures due to fatigue could result in exhaustion of life support consumables before LM ingress is achieved.

The purpose of this memorandum is to define the performance capability of the extravehicular astronaut based on his responses to fatigue in a way which can be related directly to the performance envelope of his life support system(s). The effects of environmental and temporal factors are reviewed also to provide better understanding of their influence on fatigue. Work/rest guidelines are then formulated to minimize the impact of temporal

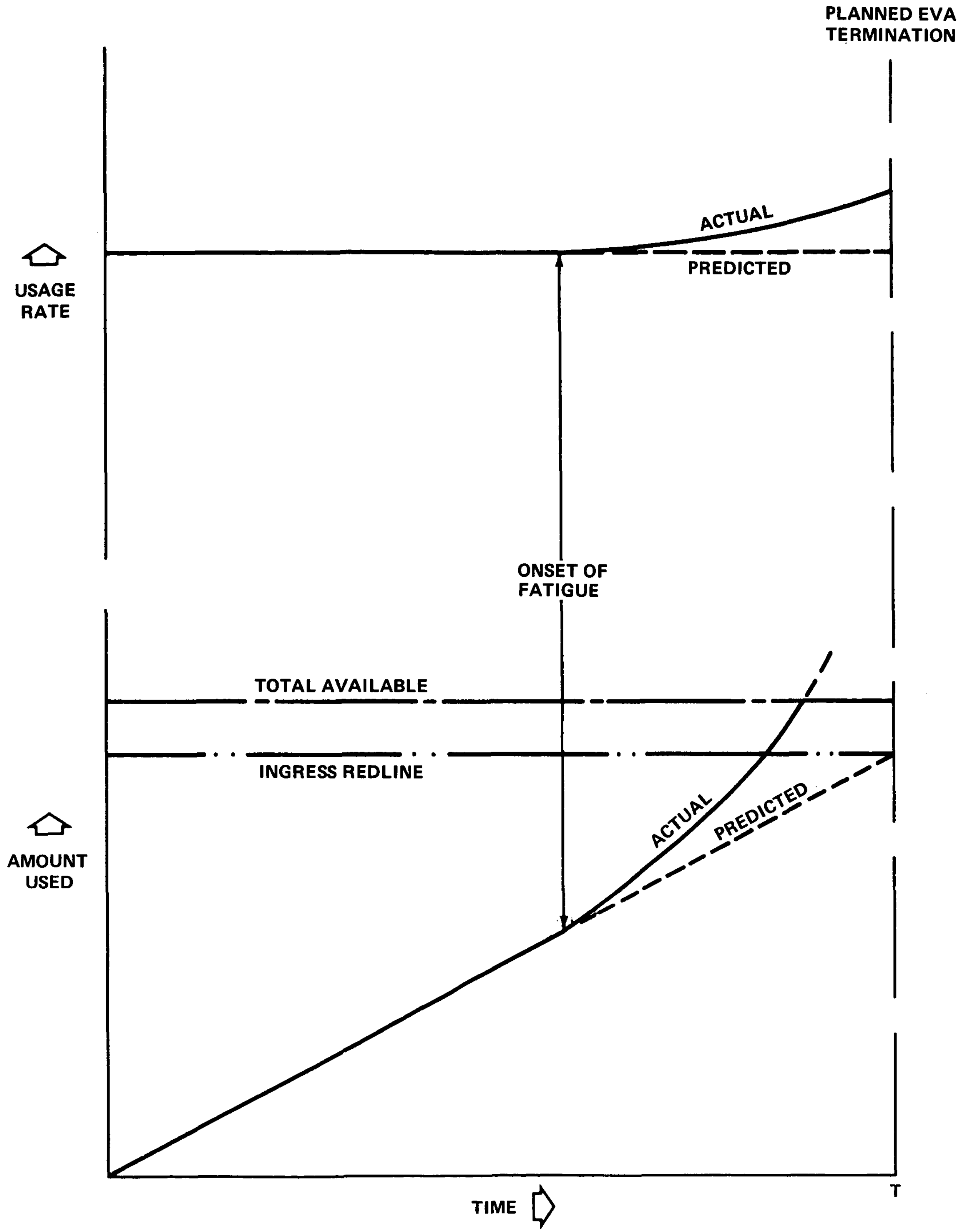


FIGURE 1 - EFFECT OF FATIGUE ON CONSUMABLES USAGE DURING EVA

factors on fatigue baselines. Data covering the effects of fatigue on the performance of unstressed subjects working for long periods of time are sparse. Accordingly, additional information is needed in order to make the fatigue limits defined herein more precise.

FATIGUE EFFECTS AND LIMITS

Fatigue is a complex factor which varies with the energy level, duration and nature of the work. It is intensified by lack of sleep, water and food, and by discomfort and environmental stresses. The effects of fatigue include actual physiological changes in the body and reduced efficiency in the performance of tasks. Mild symptoms of fatigue include irritability, inattentiveness, and a feeling of weariness. Acute symptoms include loss of motor control and short term memory, and incoherent speech.

Two boundary conditions are of interest in defining fatigue limits. These conditions are:

a) onset of fatigue, and

b) end-point for useful work.

While the onset of fatigue may be recognized by manifestations of the mild symptoms noted above, these manifestations are not considered by the author to be significant to a motivated astronaut's performance. Accordingly, onset of fatigue is defined herein as the point in time after which energy costs for the same tasks will increase (i.e. work efficiency is reduced).

The end-point for useful work has been defined in an earlier memorandum as the time when an individual will voluntarily stop work to rest in other than emergency situations.(1) This definition is not meant to apply to heavy workload transient effects such as difficulty in breathing (i.e. shortness of breath) and high heart rates (e.g. 160-180 bpm) provided that these conditions are alleviated readily by short periods (5-15 minutes) of rest. It is considered to apply to an early stage of exhaustion which may be characterized by slowed reactions, unsteadiness, mental lapses and speech difficulty (but not incoherence). When this stage of fatigue is reached, a penalty in increased energy expenditures is expected to carry over to the next day's activities.

A survey of the literature indicates that very few baseline studies have been made of the fatigue effects of active physical work over a period of more than 6-7 hours in the absence of at least one other stress. Tests have been run which involved the deleterious effects of low oxygen or high CO_2 atmospheric compositions, vibration, acceleration, and thermal stress on work capacity and endurance.[2,3,4] Studies have been made also of fatigue as a cause of error in performance of sedentary tasks requiring intense concentration and vigilance such as radar tracking and copying code. The results of these experiments have established that the nature of the work is an important factor in determining the length of time that an operator can perform efficiently. Recommended time limits for efficient performance while doing various types of work under non-stressed conditions are summarized in Table 1.[5] It can be seen that a number of the task descriptions are representative of lunar landing mission activities.

Ames Research Center Fatigue Studies

In the past five years, several long-duration human experiments have been performed at the NASA Ames Research Center to clarify the relationships between body metabolism and work performance.[6,7,8,9,10] Though particular emphasis was directed at development of special dietary supplements to prevent fatigue and improve work capacity, the data gathered during these experiments also appear to be of value in determining the operational capability of astronauts working on the moon. Unfortunately, some of these data were not included in the referenced reports in sufficient detail to permit more than semi-quantitative estimates of the effects of workload and time on specific fatigue responses. Further review of all of the experimental data and results with the Ames researchers should provide much additional information required to define fatigue limits. In the interim, the published reports provide the bases for the following discussion of the experiments and their results.

Between 20 and 27 male subjects participated in each of three experiments.[7,8,10] The total pool size was 47 subjects. They ranged in age from 22 to 43 years (mean 32.3 ± 4.2*). Their mean weight was 78.1 ± 8.4* Kgs and lean body mass ranged from 75 to 92 percent. All subjects underwent a three-month physical conditioning program consisting of 20 minutes of vigorous calisthenics followed by an uninterrupted 2-mile run each day for an unspecified period and, subsequently, three times a week.[8]

Tests were run at two levels of physical activity - resting and working at about 1/3 (i.e. 1200-1600 Btu/hr.) of each individual's maximal work capacity. The resting run was conducted with the subject lying on a couch for a period of 24 hours. Sleeping was not permitted.

*Standard deviation.

TABLE I

Recommended Time Limits for Efficient Performance for Various Types of Work [5]

Description of Work	Recommended Time Limits
Task which requires low level motor skills, is highly repetitive and devoid of critical decisions.	Up to 12 hours
Highly redundant task using standard procedures, moderate responsibility, and limited manual precision.	Up to 8 hours
*Heavy, continuous physical labor interspersed with suitable recess. (EVA)	Up to 6 hours
*Fairly responsible, decision-making task on a continuous, but random basis. (EVA)	Up to 4 hours
*Critical, but monotonous vigilance task (Driving LRV).	Up to 2 hours
*Extremely accurate motor skill with critical reaction time - no time to relax (LM Descent and Ascent).	Up to 30 minutes

*Representative of lunar mission tasks.

Work consisted of the subject walking on a treadmill for 80 minutes followed by 10 minutes rest until he was exhausted or until 24 hours had lapsed. Walking velocity varied from 4.3 to 4.8 Km/hr (2.6 to 2.9 mph) at inclinations between 0 and 1°. Each subject participated in both rest and work runs and served as his own control. Each working run for a particular subject was separated from his resting test by at least 4 weeks.

All test runs were made with the subjects in a post-absorptive (fasting) state. The subjects were provided water and salt (200 ml/hr H_2O and 1 gm/4 hrs NaCL), but not food, during the tests. In addition, temperature and humidity were adjusted to maximize comfort and to minimize water loss due to sweating. Accordingly, the only unusual stresses experienced by the Ames' subjects were sleep deprivation and lack of nutrition.

The results of these tests which appear most useful in defining fatigue limits are summarized below. Specific data are included to point up correlations (or the lack of correlations) between changes in metabolic reserves of the body and observed changes in working and resting performance.

Endurance times for the working subjects varied from 9 to 24 hours at metabolic rates which ranged from approximately 1100 to 1450 Btu/hr when the rate during rest is included in the average. The mean time to exhaustion was 982 minutes (16.4 hours) after start of the test for the entire population of 47 subjects. The mean time awake was approximately 19 hours. One day of rest was required for full recovery of the exercising subjects.

While fatigue was the usual cause for premature termination, three subjects were terminated because of undesirable cardiovascular activity. Nine subjects developed abnormal depression (more than 2 mm) of the ST segment of their EKG pattern; however, eight of these subjects were able to continue the test.[8]

The average energy deficit* during the 24-hour period of rest was about 6400 Btu's (an average of 266 Btu/hr), and during the 16.4 hours of work was about 20,800 Btu's (an average of 1270 Btu/hr).[7] The data presented in the reports were insufficient

---

*"Energy deficit" is used in place of "total energy expended" to point up that the energy is being consumed from a finite supply of metabolic energy stored in the body.

to make other than inferential qualitative and quantitative correlations between energy deficit and fatigue responses. That temporal factors, such as sleep deprivation, also have to be considered was demonstrated by the similarity in metabolic responses by both resting and working subjects (cf. Fig. 2B and 2C). The effects of sleep deprivation on performance are discussed later in this memorandum.

Slight increases in heart rate prior to test terminations suggest that fatigue may be related to decreased cardiovascular system efficiency. Persistent findings of loss of steadiness and incoherence of speech, and occasional instances of emotional instability, indicate that fatigue may be related to deterioration of the neuromuscular system and higher mental processes.[7] Either one or both of these physiological conditions may apply.

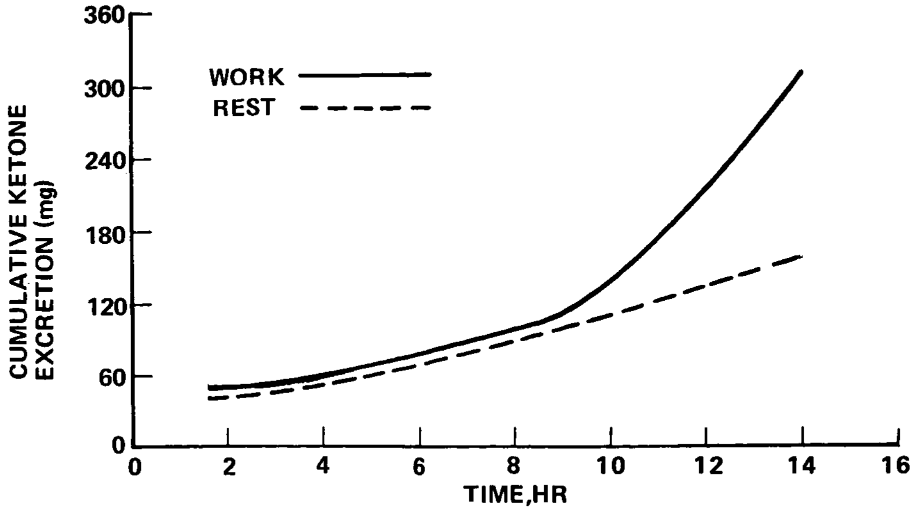
Contrary to the findings of a number of other researchers, physical exhaustion during treadmill work could not be conclusively related to variations in serum glucose and free fatty acids (FFA) in the blood, or to ketone excretion. Serum glucose and free fatty acids reached steady-state levels after about 7.5 hours working and 9 hours resting; that is, about 19 to 20 hours after the last meal. Conversely, ketone excretion by the exercising subjects only increased markedly after nine hours. These data are shown in Figure 2.[10]

The respiratory exchange ratio (R) during steady-state work remained relatively constant at values slightly less ($.79 \pm 0.04$) than resting levels (0.82 ± 0.01).[8] This result differs from that normally obtained during short periods of heavy work when R approaches 1.0 since the energy in these cases is provided essentially by the metabolism of carbohydrates.[7]

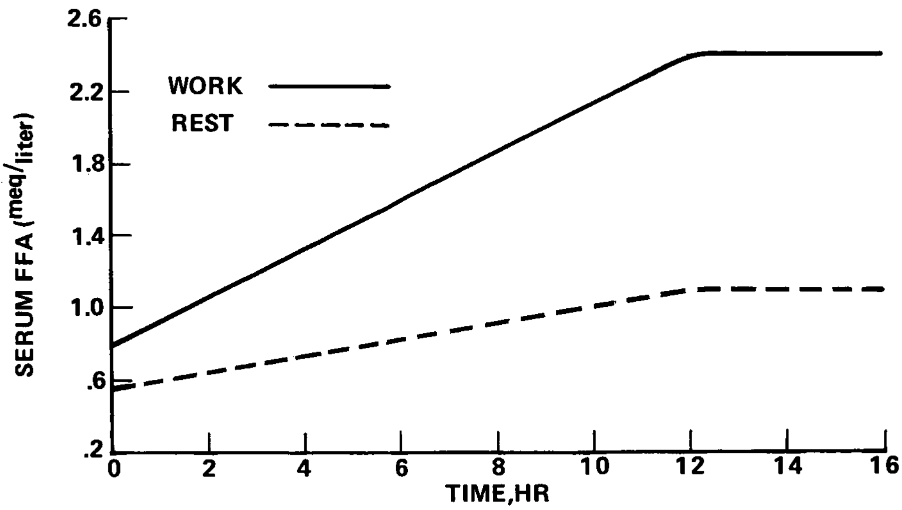
Data showing oxygen consumption during the Ames' tests were provided in one report only.[6] Oxygen consumption during the resting runs was relatively constant throughout the 24-hour period. The average metabolic rate for the resting subjects was about 320 Btu/hr (1.35 Kcal/min). However, oxygen consumption of the working subjects began rising 5-6 hours after start of the runs. The data indicate that the energy costs then increased over a period of 3 to 4 hours from an average value of about 1130 Btu/hr (4.75 Kcal/min) to a new steady-state* level of about 1260 Btu/hr (5.3 Kcal/min) or about 12%. These data are shown in Figure 3.

---

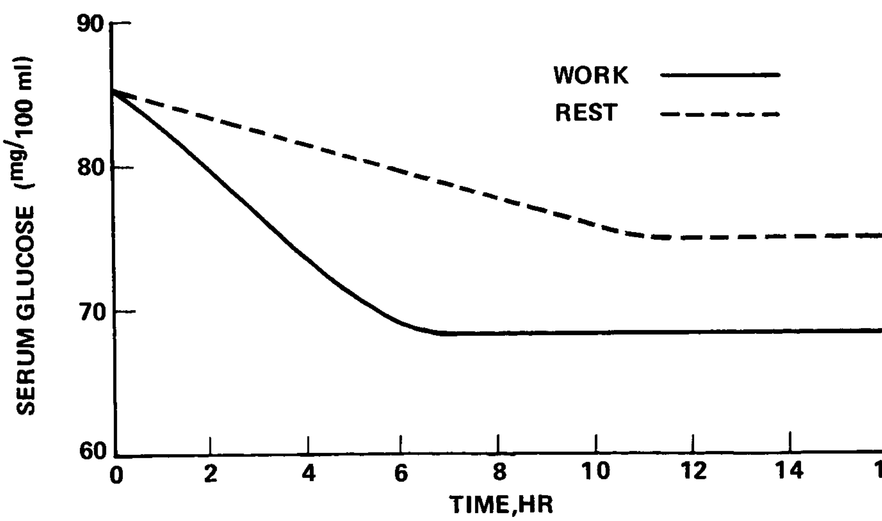
*It is uncertain if metabolic rate actually stabilized at this higher level since the pooled data were not corrected for variations caused by subjects who were terminated early.



A. CHANGE IN URINARY KETONE BODY EXCRETION



B. CHANGE IN SERUM FFA



C. CHANGE IN GLUCOSE CONCENTRATION

FIGURE 2 - CHANGES IN KETONE BODY EXCRETION, FREE FATTY ACID (FFA) AND GLUCOSE CONCENTUATIONS DURING WORK AND REST.

FROM NASA AMES DATA (7, 8, 10)

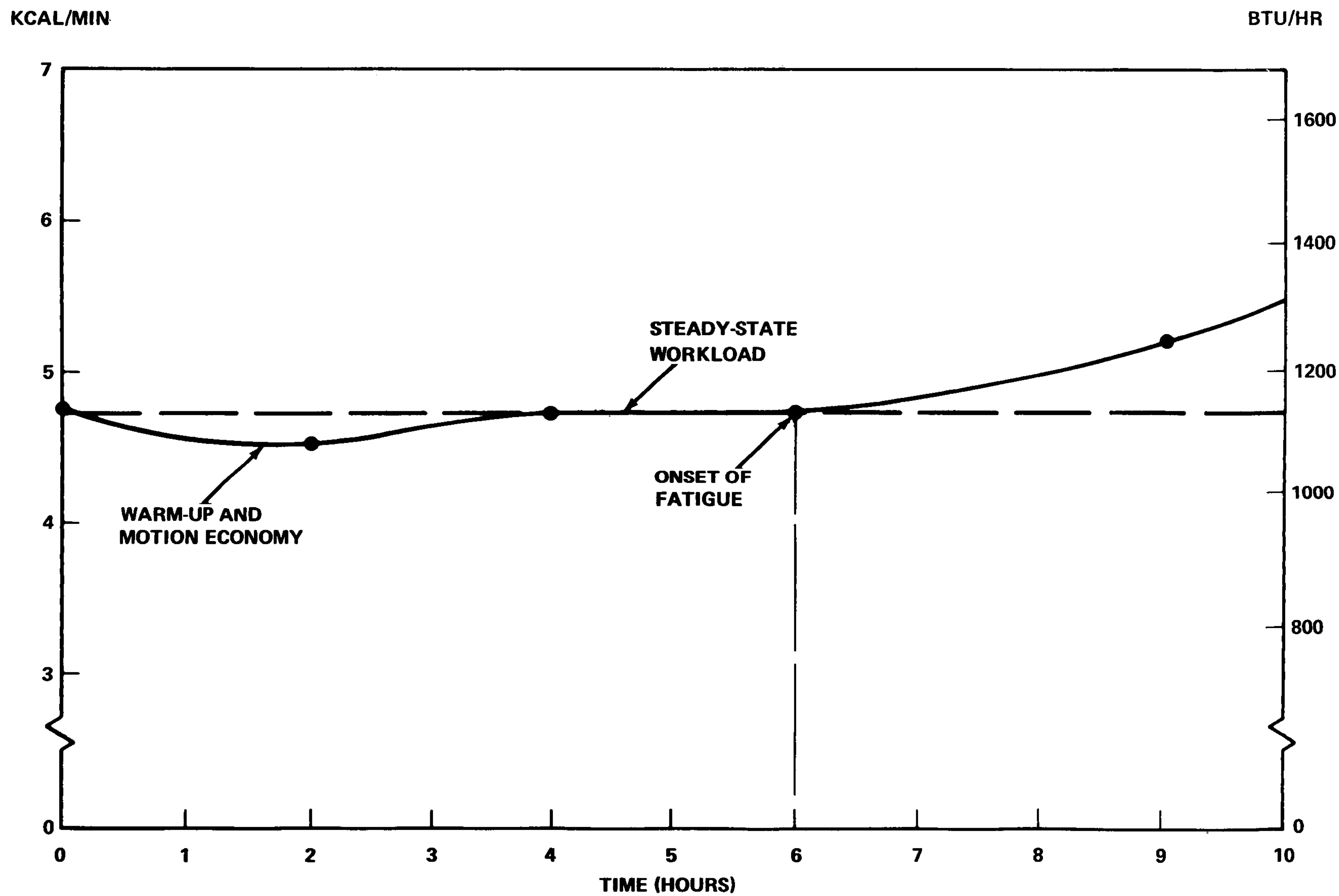


FIGURE 3 - TOTAL ENERGY EXPENDITURE RATE AS A FUNCTION OF TIME DURING CONTINUOUS (TREADMILL) WORK AT CONSTANT LOAD

FROM NASA AMES DATA (6)

Based on my interpretation of the Ames data and on expressed opinions of the authors in the basic references, the following conclusions are made:

1) Well-conditioned subjects can work without nutritive supplement at energy levels up to 1/3 of their maximal capacity for 5 to 6 hours without symptoms of fatigue.

2) Steady-state work of this nature at energy levels of 1100 to 1400 Btu/hr can be sustained for a period of 8-12 hours by well-conditioned subjects without a significant decline in phychomotor performance (short-term memory, reaction time, steadiness, etc.) and with minimal cardiovascular strain.[10]

3) Work at 1/3 of maximal capacity by well-conditioned subjects will result in "generalized fatigue" (exhaustion) in 12 to 20 hours.

4) A minimum of one full day of rest will be required for complete recovery of subjects suffering from exhaustion.[7]

In applying these results to astronauts on the lunar surface, it appears that conservatism is necessary for the following reasons:

a) Cardiovascular and neuromuscular deconditioning will have occurred during the period of weightless flight.[11,12]

b) Total awake time and the time and energy required for pre- and post-EVA activities must be factored into the overall workload.*

c) Effects which result in increased energy costs for the same work must be minimized to ensure that safe consumables margins are maintained during EVA and that subsequent EVA timelines are not penalized.

d) Locomotive exercise of the type conducted in these tests is rhythmic and tends to be self-sustaining without special effort or thought on the part of the subject. Tasks which require more whole-body motion and mental effort may cause fatigue symptoms and effects to be manifested much earlier.

---

*Current lunar mission timelines assume the LM crew is awake for 13-14 hours prior to starting the first EVA. This period includes 2 to 2.5 hours pre-EVA activity. Post-EVA activity will be 1.5 to 2 hours.

e) A sufficient reserve of metabolic energy must be maintained in each astronaut to insure that his performance capability (i.e. resistance to fatigue) is adequate to cope with stresses imposed by degraded or failed subsystems or other unforeseen contingencies.

Arguments for relaxing the fatigue constraints on EVA duration to or beyond the limits indicated by the results of the Ames tests can be made. These are:

a) The nature of the tasks to be performed during EVA are varied. While any benefit from muscle warm-up may be lost, boredom is ruled out and some muscles may be able to rest while the astronaut performs a different task.

b) The crew will eat before and after each EVA. As a consequence, metabolic energy reserves will be higher at the start of work than were those of the postabsorptive subjectives.

Considering the factors of in-flight deconditioning and the pre- and post-EVA work loads which operate to reduce an astronaut's work capacity and endurance, the results of the Ames' tests suggest that the EVA fatigue limits for the Apollo astronauts, working at an average metabolic rate of 1000 Btu/hr, should be not greater than:

a) 5 hours to onset of fatigue,

b) 8 hours to end-point for useful work, and

c) 12 hours to exhaustion.

The total energy deficits corresponding to these limits are, therefore, 5000, 8000 and 12,000 Btu's respectively. If a total of four hours pre- and post-EVA activity at an average metabolic rate of 600 Btu/hr[13] is added on, the fatigue limits defined above correspond to total energy deficits exceeding 7000, 10,000 and 14,000 Btu's, respectively.

These data have been factored in with data from other experiments and used to modify the fatigue envelopes generated in an earlier memorandum.[1] The modified envelopes are shown on Figure 4. The limits as shown are mean values and are not considered to be conservative.[19]

It is the author's opinion that the onset of fatigue boundary should be considered an operational constraint in planning EVA timelines. Relaxation of this constraint should be considered as an optional decision only to be made in realtime based on crew condition and the desirability of a tradeoff between achievement of current objectives and acceptance of reduced performance during subsequent EVAs or possible emergencies.

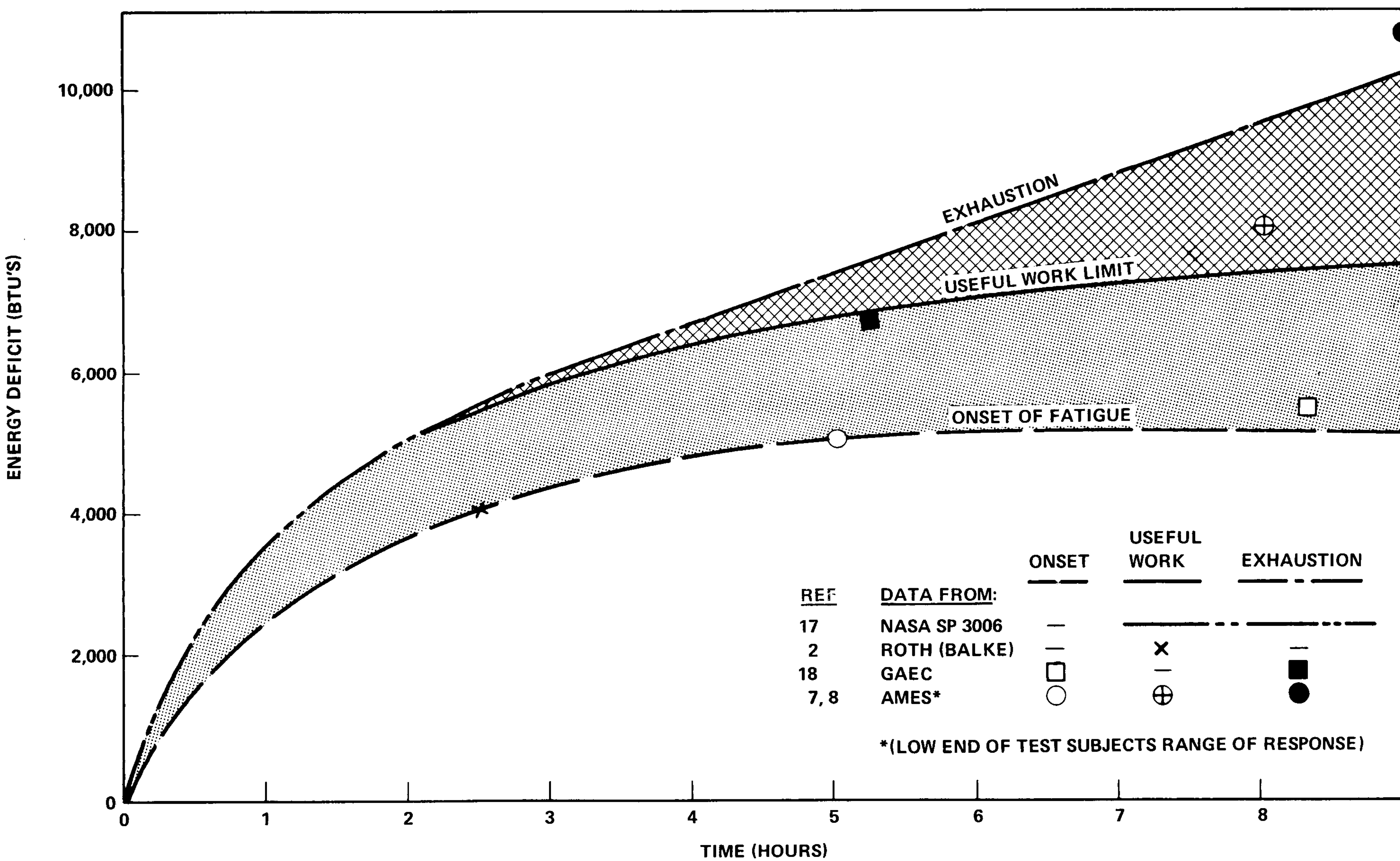


FIGURE 4 - PHYSIOLOGICAL LIMITS FOR FATIGUE

The zones between these limits are interpreted by the author in the following way. The zone between the boundaries of onset of fatigue and end-point for useful work can be penetrated without increasing risk due to an astronaut's inability to perform reliably. However, it will result in reduced task efficiency during the remainder of the work day which may carry over to the next day's activities depending on the depth of penetration. The zone between the useful work limit and exhaustion is considered to be the region in which degraded astronaut performance will result in reduced reliability and, consequently, increased risk.

Based on the information compiled from the experiments reviewed to date, it appears that Figure 4 could be divided also into three time regions. The first of these would extend from near zero to, perhaps, three hours. This region is the zone in which work rates are high (i.e. >1600 Btu/hr) and, therefore, exhaustion and useful work limits essentially coincide. Activity can be continued (at lowered efficiency) after a period of rest nearly equivalent to the period of work. Physiologically, this region is considered to be one in which the body's metabolic processes cannot keep up with oxidation demands. In particular, body fat cannot be oxidized at a rate commensurate with its degree of decomposition. The third (last) region would extend from about six or eight hours to 20 hours. In this region temporal factors (e.g. time since sleeping, eating, drinking, etc.) become overriding influences in reducing performance. The middle region, then, represents the area where it should be possible to optimize work rate and work time to obtain the most efficient performance during EVA since rest requirements can be minimized by varying tasks and pacing the work, and since temporal factors are not effectual.

It must be emphasized that the limits shown on Figure 4 have been established by extrapolation from meager information. While the results of the different experiments appear to correlate fairly well, additional data are needed to improve understanding and make the limits more precise.

The -7 PLSS limits in Figure 5 were developed by MSC to show the EVA operational envelope based on consumables usage. The onset of fatigue and useful work boundaries of Figure 4, which reflect the limits for consumption of metabolic reserves stored in the astronaut, have been superimposed on Figure 5. These plots indicate that the -7 PLSS comes close to satisfying the desired objective of providing a life support system which exceeds, in terms of metabolic capacity, the work capacity of the man.

Also shown is the effect on life support consumables margins and on mission length of an increase in metabolic rate due

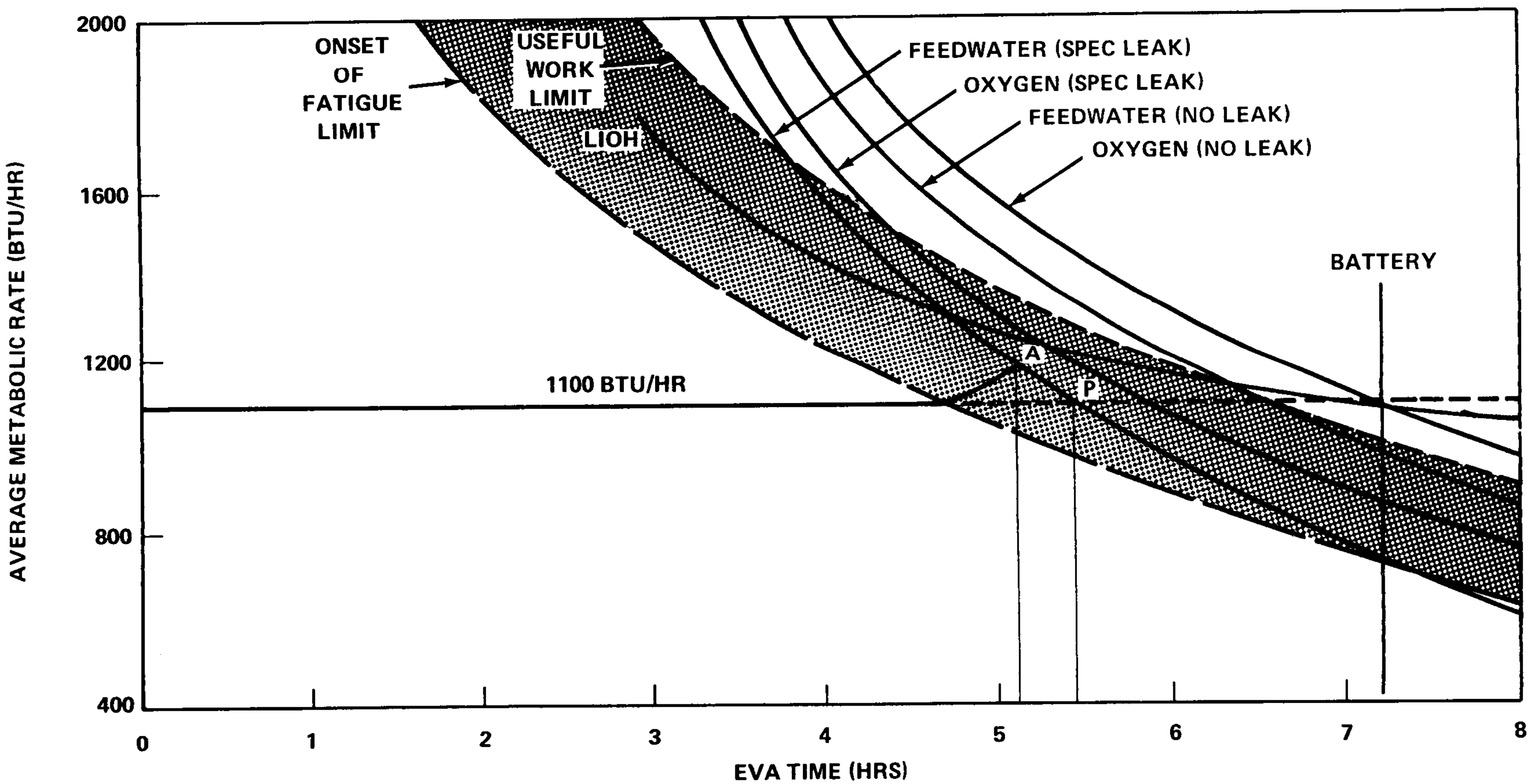


FIGURE 5 - CREW FATIGUE LIMITS AND EFFECT ON - 7 PLSS CONSUMABLES USAGE

to crossing the onset of fatigue boundary. Point P indicates the predicted time of exhaustion of feedwater based on trending expendibles consumption at an average going rate of 1100 Btu/hr. Point A is the actual time when feedwater will exhaust if metabolic rate is increased as a result of fatigue. If the effect is as severe as illustrated in this example, it could lead to premature activation of the back-up life support system. This action would necessitate a change in strategy during subsequent EVAs.

ENVIRONMENTAL STRESS

Stressful environments are inherently fatiguing as they generally cause increases in metabolic energy demands. If the stress is sufficiently intense, concomitant degradation of the physiological mechanisms which are required to maintain homeostasis can result in a degenerative situation. In this event, the time until fatigue effects occur is drastically reduced.

An analysis was made of the results of a series of fatigue tests conducted by the AiResearch Corporation[14] in which it seems evident that the subjects' performances were compromised by heat stress as well as fatigue. The following is a brief discussion of the results of the tests and my analysis.

AiResearch Fatigue Tests

Two special subjects were selected to make runs at velocities of 8, 9.7, 11.3 and 12.8 km/hr on a 1/6 g inclined plane simulator. Each subject wore a Gemini suit pressurized at 18.2 psia and a 75 pound pack. Dry air at a temperature of 50°F and flow rate of 12 cfm was provided at the suit inlet for thermal control. The duration of each run was planned for four hours unless terminated earlier due to exhaustion.

The data from the test runs are plotted on Figure 6. Only one data point is shown for the 8 km/hr run (IV) at the time when the subject lost stability control and was unable to continue. The other data points for this run were discarded by the writer as unexplained anomolies which were not consistent with the results of one-hour tests, or the extended fatigue tests at higher velocities, even though the same subjects were involved.

Only one subject was able to complete the full 4-hour run at a velocity of 9.7 km/hr. He was completely exhausted and did

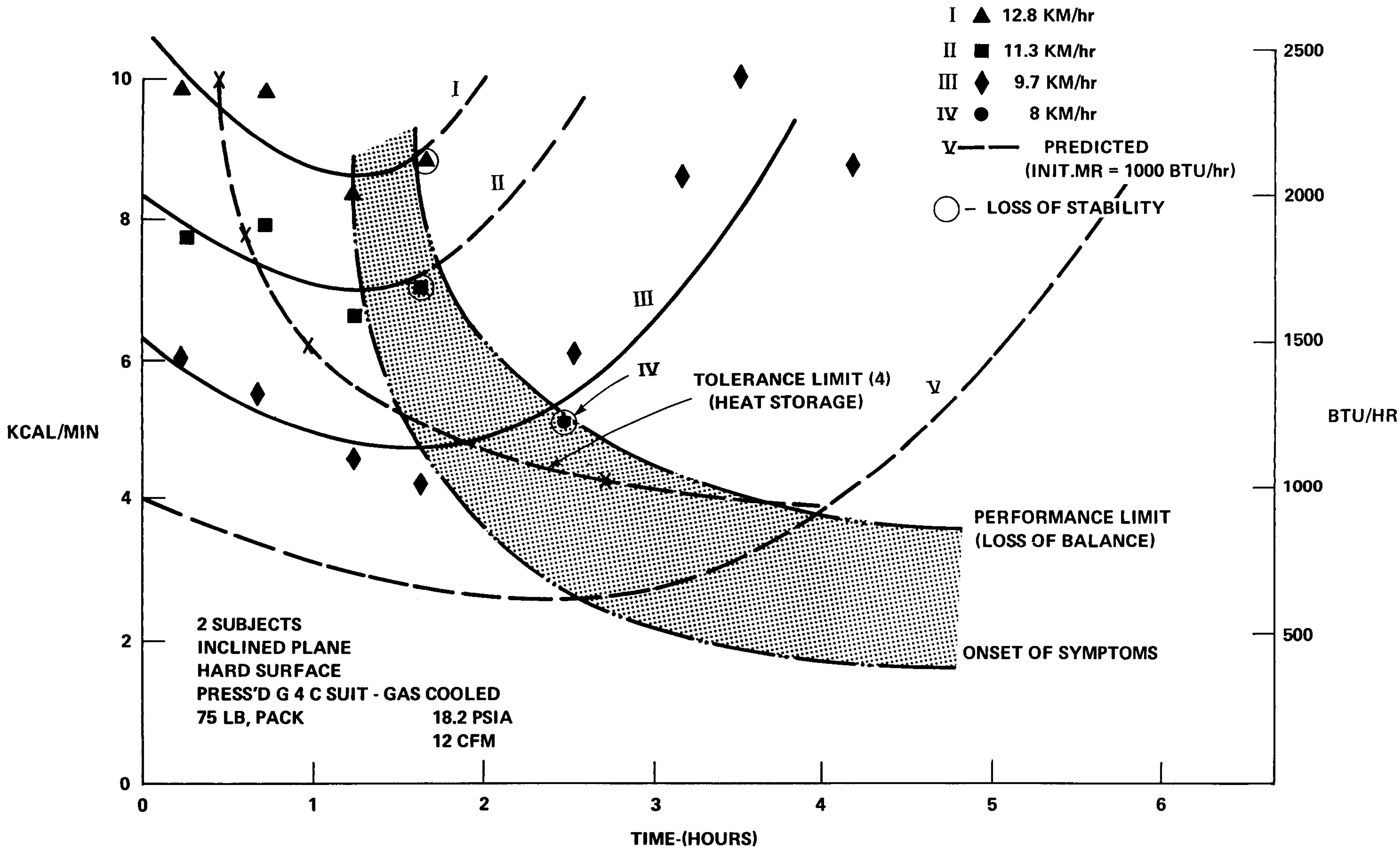


FIGURE 6. METABOLIC RATES DURING FATIGUE TEST AT SUSTAINED WORKLOADS

BASED ON DATA FROM WORTZ (REF 14) & BLOCKLEY et al (REF 4) not recover until the fourth day after the test run. In all other cases, the subjects lost stability control and fell at the times indicated by circled points on Figure 6. These runs had to be terminated because the subjects were unable to maintain balance and continue. The locus of circled points, therefore, determines a performance limit for work due to loss of balance.

Comparison of these curves with plotted data from the Ames experiments (Figure 3) shows two areas of similarity which reinforce interpretation of the data in the manner advanced in this study. Specifically, the downward slope (i.e. reduced energy cost for the same work), which indicates an increase in efficiency due to warm up, and the upturn in metabolic rates, which indicates a decrease in efficiency due to the effects of fatigue, are evident in both sets of data. In Figure 6, the locus of points where metabolic rate is a minimum and thereafter increases is considered to define the boundary for onset of fatigue.

One major difference in the results of the two studies is that the AiResearch subjects, when working at approximately the same metabolic rate as the Ames subjects, succumbed to fatigue much sooner though both groups were in excellent physical condition. The disparity in results can be traced to the inadequacy of gaseous cooling for thermal control of pressure-suited subjects working at high metabolic rates. Two indicators of thermal stress, sweat rate and heat storage, were evaluated to check on this hypothesis.

Psychometric evaluation of the change in enthalpy of the air between suit inlet and outlet under ideal conditions of mixing and sweat evaporation indicates that the maximum cooling capability of the AiResearch thermal control mode is about 1600 Btu/hr. The sweat rate to achieve this amount of cooling must approximate 0.9 lbs/hr. Sweating at this rate will result in a Heat Stress Index (HSI) of 39 which, by definition, borders on severe heat strain. At this level of stress, measurable decrement in physical performance of well-conditioned subjects can be expected to occur.[20] The definition and the calculations of HSI for this case are contained in Attachment A.

The data covering actual suit outlet conditions for the AiResearch fatigue tests were not provided. Accordingly, an outlet air temperature of 85°F, which corresponds closely to the maximum value obtained in numerous gas-cooled suit experiments, was assumed. Heat storage and time to reach tolerance limits were calculated from the heat balance equation using empirically derived expressions for the various heat exchange modes. The calculations and results are contained in Attachment B. The results have been plotted on Figure 6 (Tolerance Limit-Heat Storage) and show that there is good reason to believe that heat stress was significant, and might have been the dominating effect, in causing exhaustion.

The data shown on Figure 6 are of special interest to Apollo for two reasons.

1. They demonstrate the need for conservatism in operational planning to ensure that adequate performance margins are provided to compensate for stresses resulting from unanticipated equipment failure or debilitating environments.

In the event that the primary thermal control system fails during lunar EVA, the astronauts will use the Buddy Secondary Life Support System (BSLSS) during their return to the LM. Recent analyses show that the crewmembers will not experience heat storage at metabolic rates below 1350 Btu/hr.[21] Based on 1/6 g simulations, a rate of 1350 Btu/hr is achievable at a walking velocity of 3.5 km/hr.

2. They underline the need for understanding and programming the workload for in-flight EVA science tasks at levels which can be accommodated by the thermal control capability of the life support system.

Thermal control during inflight EVA is provided by gaseous cooling. Preliminary studies made by MSC indicate that average metabolic rates should not exceed about 1000 Btu/hr during this activity in order to avoid heat storage.[22] It should be noted that most of the cooling during inflight EVA depends on successful evaporation of sweat and that a sweat rate approximating 0.7 lbs/hr is required for thermal equilibrium at a metabolic rate of 1000 Btu/hr. This will result in a Heat Stress Index (HSI) of 32 which is defined in the literature as moderate heat strain. Subtle to substantial decrements in performance may occur if the tasks demand higher intellectual functions, dexterity or alertness.[20]

SLEEP DEPRIVATION

Sleep deprivation is an important factor which must be considered also in defining the boundary conditions for fatigue. Some insight is provided by effects observed during the Manhigh chamber tests and balloon flights. Continuous awake times varied from about 40 hours for the chamber runs to a maximum of 47 hours for the Manhigh II flight. Actually, during the flight, about two hours sleep was obtained by means of "catnaps".[15]

Briefly, the following effects were noted during the Manhigh flights:[15]

a) Initiative and response to observational opportunities continually decreased as flight time progressed.

b) Performance declined significantly due to fatigue after about 24 hours of on-duty time. After this period, only a small fraction of carefully planned observations were made and one significant event (which normally would have been photographed and taped) was noted mentally only.

c) The pilots' subjective ratings of their personal condition were extremely over-optimistic throughout the flights. The rating scale was 0-100 with a rating of 50 intended to indicate normal efficiency under ordinary conditions. On Manhigh II, the pilot's subjective ratings were never lower than 90; and, were 95 and above on the second day when actual performance was poor.* On Manhigh III, the pilot experienced severe hyperthermia without recognizing the seriousness of his condition until it was brought to his attention by ground monitors. Pilot cooperation with the ground was excellent, however, during premature termination of the flight.

d) Hallucinations were experienced during the Manhigh chamber runs but no mental aberrations were observed during the actual flights.

e) Post-test and post-flight physical effects persisted through the next day. The subjects felt physically weak such that even light exercise required much effort and was very tiring.

Similar effects were noted in a series of 30-hour space flight simulations conducted by the Air Force.(16) These tests demonstrated also that an acceptable level of proficiency could not be maintained for the entire "flight" due to biological effects of circardian periodicity and fatigue. Because of fatigue, a drastic decline in proficiency usually was observed about 20 hours after the start of a test.

The effect on proficiency of a sudden increase in workload imposed on nine test subjects about 19 hours into a 24 hour run was also evaluated by the Air Force experimenters. The results, however, were inconclusive. The performance of three subjects was unchanged; three improved slightly and three showed a decline.(16)

The Air Force simulations and Manhigh tests support the findings from other studies that even a short period of rest (i.e. 5 to 30 minutes) will result in some performance recovery. The period over which recovered performance could be maintained at acceptable levels depended on the length of the rest period and

---

*Post-flight tape runs verified this inconsistency to the pilot's satisfaction.

the total elapsed time since the last extended sleep period. If the time after awakening from sleep was long (e.g. greater than 20 hours), the improvement in performance following a brief rest could not be sustained for any appreciable period. It was not possible to make quantitative estimates of acceptable performance duration as a function of time after sleep and duration of brief rest from the available data. It seems worthwhile to explore this area in depth in order to determine if scheduling several hours sleep in the middle of a long day is a desirable precaution against degraded performance during critical operations or time-extending emergencies (e.g. the second of two back-to-back EVA's or LM abort, etc.)

WORK/SLEEP REQUIREMENTS

There is general (but not unanimous) agreement in the literature that daily activities, including sleep, should be programmed to agree with the crew's normal 24-hour circadian cycle. Variations within prescribed limits, up to ± 4 hours depending on circumstances, will not result in degraded performance.[5,16]

Based on the foregoing discussion and a number of uncited sources, the following guidelines are suggested for use in planning Apollo LEP missions:

1. Total day length, including sleep, shall be not less than 20, or more than 28 hours, during nominal operations.

2. At least one period of uninterrupted sleep shall be scheduled during each day. The period of sleep may vary from six to nine hours but shall not be less than eight hours in any day 24 or more hours in length.

3. Contingency planning should ensure that, in event of an emergency, continuous awake time of the crew shall not exceed 24 hours and shall be followed by a minimum of six hours uninterrupted sleep. In the event this guideline cannot be satisfied, one or more short sleep periods of not less than 2 hours each shall be provided at any convenient time after the crew has been awake for 12 hours or more. The goal, during contingencies, shall be to provide each crew member a minimum of six hours sleep during each 30-hour period.

SUMMARY OF RESULTS

In summary, the results of this study indicate that Apollo astronauts can work at an average metabolic rate of 1000 Btu/hr on the lunar surface for approximately five hours with no reduction in efficiency due to fatigue. Continuation of EVA beyond the 5-hour onset-of-fatigue limit is expected to result in an increase in life support consumables usage due to lowered astronaut efficiency. Accordingly, it is proposed that the onset-of-fatigue boundary be considered an operational constraint on EVA duration for planning purposes.

It is concluded, also, that EVA crewmen can perform reliably for about eight hours at the 1000 Btu/hr work level. This 8-hour limit is defined as the end-point for useful work beyond which crew risk is increased by slowed reaction time, loss of steadiness and reduction in mental facility. Extension of EVA duration into the zone bounded by the onset of fatigue limit and the end-point for useful work limit is expected to result in carryover of fatigue effects to the next day's activities. It is suggested, therefore, that extension of EVA beyond five hours be made a real-time decision which considers the crews' condition and weighs the tradeoff between completion of important mission objectives versus the requirement for undegraded crew performance during later planned activities or unforeseen emergencies.

Other factors which influence the effects of fatigue, such as heat stress and sleep deprivation, argue for conservatism in establishing fatigue boundaries. Heat stress is not a problem if life support systems are performing nominally during lunar surface excursions. However, walking velocity must be limited to about 3.5 km/hr to avoid heat storage in the case of failure of the primary thermal control system during lunar EVA. During in-flight extravehicular activity average metabolic rate must be controlled to about 1000 Btu/hr to avoid heat storage due to performance limitations of the gaseous cooling mode.

Sleep deprivation effects, though easily avoided by exercising reasonable care in timeline scheduling for the nominal mission, deserve special consideration in analyses dealing with cases of potential abort which may depend for their success on optimal crew performances. The work/rest guideline proposed in this memorandum for the nominal mission timeline (i.e. 24 $\pm$ 4 hours day length including 8 hours sleep) is in general accord with that recommended by MSC/MROD. The work/rest guideline suggested for contingency planning purposes (i.e. a minimum of 6 hours accumulated sleep in each 30-hour period) is felt to be conservative but may require further study.

Finally, it must be recognized that the fatigue limits as defined and quantified in this report are based on data which are sparse for periods of exercise beyond one hour.(17) These limits can be better understood and made more precise by running long duration tests which complement and expand the data base established by the NASA Ames Research Center.(6)

Experiments conducted with unstressed astronaut-like subjects working at several levels of light-to-moderate steady state workloads for periods up to 20 hours would provide meaningful data. Changes in physiological parameters (e.g. oxygen consumption, cardiac output, ketone excretion, etc) should be measured and time-correlated with observed changes in subject performance (e.g. mental acuity, unsteadiness, speech difficulty, etc). The underlying objective of the tests should be to improve confidence that LEP objectives can be achieved without increasing crew risk because of unacceptable degradation in astronaut performance.

T. A. Bottomley

2032-TAB-tla T. A. Bottomley

Attachments

ATTACHMENT A

Computation of Heat Stress Index

This analysis assumes that the subjects perspired profusely and by means of this mechanism minimized heat strain from heat storage and elevated body temperature. Reliance on evaporation of sweat as the main mode of heat exchange maximizes the effectiveness of gaseous cooling at the expense of dehydration.

The test subjects were gas-cooled with 50°F (dry) air at a suit pressure of 3.5 psig (18.2 psia). The ventilation flow rate was 12 cfm (65 lbs/hr). The outlet conditions were not given in the basic report (Reference 14). The total heat removed is a function of the change in enthalpy (ΔH) of the gas stream between suit and outlet conditions.

Heat stress calculated from change in total enthalpy (H):

Suit conditions:

Inlet air:	T=50°F (dry)	H=11 Btu/lb dry air
Outlet air: (Assumed)	T=85°F; RH=85°*	H=36 Btu/lb dry air

*Specific humidity = .016 lbs H_2O/lb dry air

Total heat removed = $W_g \, \Delta H$ (Btu/hr)

where W_g is the mass flow of gas (lbs/hr)

= 65 (36-11)

= 1625 Btu/hr

Total Water Loss Rate = 65 x .016 = 1.04 lbs/hr

The total water loss is equal to the sweat loss plus water lost via respiration. Respiratory water loss is assumed constant at 0.18 lbs/hr. (17)

The Heat Stress Index (HSI) is defined as the ratio of actual sweat rate to maximum permissible sweat rate (2.2 lbs/hr) x 100, or equivalently for this case:

$$HSI = \frac{\text{Total water loss rate less respiratory loss rate}}{\text{Max. permissible sweat rate}} \times 100$$

$$= \frac{(1.04 - 0.18)}{2.2} \times 100$$

$$=39$$

A HSI of 39 is at the lower bound of severe heat strain in which some decrement of physical performance is to be expected.[20]

ATTACHMENT B

Computation of Heat Storage and Tolerance Time

The heat balance equation is:

$$Q_s = Q_m - (Q_e + Q_c + Q_v + Q_r) \text{ in Btu/hr}$$

where Q_s = heat storage
Q_m = metabolic rate
Q_e = evaporative cooling rate
Q_c = convective cooling rate
Q_v = respiratory cooling rate
Q_r = radiation heat exchange

Suit Conditions

Inlet air:	50°F; dry
Outlet air:	85°F (assumed)
Pressure:	18.2 psia
Flow rate:	12 cfm (65 lbs/hr)

Q_r (negligible due to the suit insulation) = 0

$$\begin{aligned} Q_c \text{ (essentially constant)} &= Wg\ CP\ \Delta T \\ &= 65 \times 0.24\ (85-50) \\ &= 545 \simeq 550 \text{ Btu/hr} \end{aligned}$$

Q_e and Q_v are functions of metabolic rate and have been established empirically to be:[20]

$$Q_e = 0.125\ Q_m + 50$$
$$Q_v = 0.25\ Q_m$$

The time to reach heat storage tolerance limits is expressed:[4]

$$\theta_t = \frac{400}{Q_s} \text{ (hours)}$$

The results of the calculations are summarized as follows:

Q_m	Q_c	Q_e	Q_v	$(Q_c + Q_e + Q_v)$	Q_s	Q_t (hours)
2400	550	350	600	1500	900	0.45
2000	550	300	500	1350	650	0.6
1600	550	250	400	1200	400	1.0
1200	550	200	300	1050	150	2.7

REFERENCES

1. Bottomley, T. A. "EVA Metabolic Capacity Required for LEP Life Support Systems" - Case 320 Bellcomm Memorandum for File B69 08030, dated August 11, 1969.

2. Roth, E. M. Sect. 10: Oxygen - CO_2 - Energy in "Responses to the Aerospace Environment" NASA CR-1205, Washington, D.C., November 1968.

3. Informal Communication from Captain David Morris, USN, Aerospace Medical Research Laboratory, Johnsville, Pa., on February 25, 1970.

4. Blockley, W. V., McCutchan, J. W., Taylor, C. L., Prediction of Human Tolerance for Heat in Aircraft: A Design Guide WADC - TR-53-346, May 1954.

5. Woodson, W. E. and Conover, D. W., Human Engineering Guide for Equipment Designers, University of Calif., Press, Berkeley, Calif., 1964.

6. Young, Donald R., Study of Effects of Carbohydrates on the Body Under Stress and Fatigue, NASA SP-70, Conference on Nutrition in Space and Related Waste Problems, 1964.

7. Young, D. R., Pelligra, R and Adachi, P. R. Serum Glucose and Free Fatty Acids in Man During Prolonged Exercise, J. Appl. Physiology, Vol 21, No. 3, May 1966.

8. Shapira, J., Young, D. R., Datnow, N. B. and Pelligra, R., Development of a Standard Prolonged Work Test for the Evaluation of Fatigue and Stress in Man, Aerospace Medicine, Vol 38, No. 3, March 1967.

9. Young, D. R., Shapira, J., et al Model for Evaluation of Fatty Acid Metabolism for Man During Prolonged Exercise, J. Appl. Physiology, Vol 23, No. 5, November 1967.

10. Young, D. R., Pelligra, R., etal, Glucose Oxidation and Replacement During Prolonged Exercise in Man, J. Appl. Physiology, Vol 23, No. 5, November 1967.

References

11. Berry, C. A. and Catterson, A. D., Pre-Gemini Medical Predictions versus Gemini Flight Results, Gemini Summary Conference Report SP-138, MSC, Houston, Texas, February 1-2, 1967.

12. Berry, C. A. Medical Aspects of Apollo VII and VIII, Aerospace Medicine 40:3, March 1969.

13. Rodriguez, M. and Kincaide, W. C., Master End Item Specification... Extravehicular Mobility Unit, CSD-A-096 (Rev. A), MSC, Houston, Texas, May 7, 1968.

14. Wortz, E. C., Robertson, W. G., Browne, L. E. and Sanborn, W. G. Man's Capability for Self-Locomotion on the Moon, Vol I. AiResearch Report 68-3986, Rev. 1, for LaRC, NASA, Washington, D.C., March 1969.

15. Simons, D. G., Henderson, B. W. and Riehl, J., Personal Experiences in Space Equivalent Flight in "Psychophysiological Aspects of Space Flight", Columbia University Press, New York, 1961.

16. Hauty, G., Psychophysiological Problems in Space Flight in "Bioastronautics", MacMillan Co., New York, 1964.

17. Webb, P. Bioastronautics Data Book, NASA SP-3006, Washington, D.C., 1964.

18. Grumman Aircraft Engineering Corporation, Lunar Surface Scientific Mission Simulation (3 vols) November 1967.

19. Informal discussions with Drs. F. B. Benjamin and R. R. Hessberg, NASA/MM.

20. Bottomley, T. A. and Roth, E. M., Ch. 6 Thermal Environment in "Compendium of Human Responses to the Aerospace Environment" NASA CR 1205(I) Washington, D.C., November 1968.

21. Bottomley, T. A. Trip Report: Critical Design Review of Apollo Portable Life Support Systems, Case 320, Bellcomm Memorandum B70 06032 dated June 8, 1970.

22. Bottomley, T. A. Trip Report: Inflight EVA Steering Committee Meeting #2, Case 320, Bellcomm Memorandum B70 06078, dated June 25, 1970.

DISTRIBUTION

COMPLETE MEMORANDUM TO

CORRESPONDENCE FILES:

OFFICIAL FILE COPY
plus one white copy for each
additional case referenced

TECHNICAL LIBRARY (4)

NASA Headquarters
F. B. Benjamin/MM
R. Hessburg/MM
J. W. Humphreys/MM
T. A. Keegan/MA-2
C. H. King/MAT
C. M. Lee/MA
T. H. McMullen/MA
R. A. Petrone/MA
A. F. Phillips, Jr./MAT
L. R. Scherer/MAL
W. E. Stoney/MA

NASA Ames
J. Billingham/LT
D. R. Young/LTB

MSC
L. E. Bell/EC6
C. A. Berry/DA
A. D. Catterson/DA
H. R. Hair/DA
W. J. Huffstetler/EC6
W. E. Hull/DA
G. F. Humbert/DD5
E. L. Hays/EC
R. S. Johnston/AC
J. P. Kerwin/CB
R. L. Kubicki/PD
R. E. Mayo/EC
J. A. McDivitt/PA
H. J. McMann/EC6
E. L. Michel/DB
N. Prince/EC6
J. R. Sevier/PD
R. E. Smylie/EC
H. L. Stutesman/EC9
K. L. Thomas/PT2

COMPLETE MEMORANDUM TO

Boeing (Houston)
Lowell Nelson

GAEC (Bethpage, N.Y.)
Thomas Gleason

TRW Systems (Houston)
D. Appleton
R. Diamond
J. A. Herbaugh

Bellcomm, Inc.
D. J. Belz
A. P. Boysen
F. El-Baz
D. R. Hagner
N. W. Hinners
A. N. Kontaratos
J. Z. Menard
G. T. Orrok
P. F. Sennewald
L. D. Sortland
W. Strack
R. L. Wagner
Department 2032
Department 1024 File
Central Files
Library

COVER SHEET ONLY TO

J. P. Downs
J. J. Hibbert
I. M. Ross
R. V. Sperry
J. W. Timko
M. P. Wilson